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THE PROBLEM OF THE ANORTHOSITES

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STATEMENT OF THE PROBLEM

Seldom can it be truly said that the puzzling feature of any object is its simplicity, yet of all the problems that the anorthosites present to us for solution the most difficult is their simple mineralogical composition. Bunsen long ago taught geologists to think of rock magmas as solutions, and the so-called solution theory[1] of magmas has now gained general acceptance. We have been enabled to understand many features of magmas that without the aid of the theory of solutions would remain incomprehensible. We understand why the order of separation of mineral from a magma is not simply the order of their fusibility. We understand also why a rock magma remains liquid at temperatures far below the temperatures of fusion of the individual minerals that enter into the magma and, therefore, why magmatic temperatures are comparatively moderate. It is because the individual minerals exist in the magma in mutual solution and therefore have their specific properties modified. But when we turn to anorthosites we find

[1] Nowadays it is scarcely proper to speak of the solution theory of magmas, for magmas are solution in virtue of the definition of a solution rather than by theory. On the other hand, to speak of the theory of solutions as applied to magmas is, of course, entirely permissible.

them made up almost exclusively of the single mineral, plagioclase. What, then, of the magmatic temperatures of anorthosites? Have we in them an exception to the rule of moderate magmatic temperatures?

Anorthosites apparently exert no exceptional influence upon surrounding rocks. Foreign inclusions, even very susceptible ones, are apparently not melted up. Inclusions of quartz-bearing rocks do not have their quartz changed to tridymite or cristobalite. Nothing in the field evidence gives us any reason to believe that anorthosites are in any way exceptional in this respect. Neither do we find any comfort in field evidence if we entertain the possibility that, in the absence of other minerals in amounts adequate to produce a great lowering of the melting temperature of plagioclase, there was present instead a sufficient amount of the much more potent "mineralizers." Typical anorthosite is notably free from all those minerals which, when present in rocks, constitute the principal evidence of the presence of volatile components in significant amounts in their magmas.[1]

An alternative possibility is that the material of anorthosites actually was in solution in something else at one time and that it differentiated from this solution. This alternative is more in harmony with general opinion, for few would state that beneath those places where we find anorthosites, there existed some anorthosite magma and that it simply was always there. It is generally believed, rather, that anorthosites are differentiates of gabbroid magma, the belief being based on field association. But it is also commonly believed that the differentiation took place in some manner in the liquid state and produced anorthosite magma. Now we must realize, and face the fact squarely, that anorthosite magma, however produced, is, nevertheless, anorthosite magma, and must exhibit the appropriate characteristics. It could separate as a liquid, by any process whatsoever, only at temperatures at which it could exist as a liquid, and we are immediately presented with precisely the same temperature problem. Anorthosites, as we have seen, do not give evidence of ever being at a temperature approaching that requisite to melt plagioclase.

[1] This matter is considered in greater detail in connection with the Morin anorthosite.

THE PROPOSED SOLUTION

For this reason in part, but also because careful consideration of all the possibilities and much experimental work to test these possibilities seem to indicate the inadequacy of any process other than crystallization, it is believed that the gabbroid magma must proceed to crystallization, and that anorthosite masses are simply collected plagioclase crystals. It is believed, then, that anorthosites were never liquid as such, but that their material when liquid was part of a solution probably of a gabbroid nature. Only in virtue of the sorting of solid, crystalline units from this solution does anorthosite come into being.

Having arrived at this belief, we may examine the anorthosites to see in how far they agree with its consequences, but before this can be done it is necessary to discuss in detail the process of sorting of crystals.

THE PROCESS OF ACCUMULATION OF CRYSTALS

General relations involved.—It must be admitted that the problem of the method of accumulation of plagioclase crystals for the formation of a mass of anorthosite is not a simple one. If the plagioclase crystals were much heavier or much lighter than gabbroic magma, all would be plain sailing. It could then be assumed that the crystals sank in the magma or floated in it, and were therefore accumulated at the bottom or at the top. But laboratory determinations of the densities of calcic plagioclase crystals and of molten gabbro place them very close together, with the crystals a very little lighter, and while the difference would not be the same and might even be in the opposite direction, there is, nevertheless, every reason to believe that it would still be small under natural conditions. As a matter of fact, we actually find this similarity of density expressed in the composition of anorthosites. If plagioclase were much lighter or much heavier, the mere accumulation of crystals would be, as we have seen, a simple matter, but the anorthosite masses formed would not be such as we find them, a fact which will become obvious from the following considerations.

During the crystallization of a magma involving the precipitation of mix-crystals the crystals first deposited are rich in the higher-

melting component of the mix-crystal series. As the magma cools, especially if it cools very slowly, these crystals continually change in composition as a result of interchange of material between liquid and crystals, the change being always in the direction of enrichment in the lower-melting component. But this change is fully accomplished only when adequate liquid is available. If the crystals are heavy and accumulate toward the bottom, the small amount of liquid there available cannot continue indefinitely to enrich the crystals in the lower-melting component. They therefore remain very rich in the higher-melting component, increasingly so the greater the preliminary accumulation of crystals. Vogt's important statistical study of the anchi-monomineralic rocks shows quite definitely that in the case of peridotites the ratio of Mg_2SiO_4 to Fe_2SiO_4 in the olivine increases directly with the proportion of olivine in the rock.[1] The orthorhombic pyroxenes apparently follow a parallel law.

This is, then, precisely as deduced above for rocks formed by the accumulation of heavy early crystals. If plagioclase were a very heavy or a very light mineral, we should find a similar relation to hold for it, namely, the greater the proportion of plagioclase in a rock, the greater would be the proportion of anorthite in the plagioclase. But when we turn to Vogt's similar study of anorthosites, we find in them a quite different tendency. The richer a rock is in plagioclase, the greater the tendency for the plagioclase to be, not a very calcic one, but the intermediate one, labradorite.[2] This character of the plagioclase is, it is believed, directly connected with the fact that the plagioclase being precipitated from gabbroic magma sensibly matches the magma in density. It is perhaps slightly lighter than the magma, but usually not sufficiently so to cause it to accumulate locally and to form masses of crystals much enriched in the higher-melting component as do olivine and pyroxene. Instead, it remains practically suspended in the liquid, with probably a very slight tendency to rise at first, and the whole of the liquid is available for the production of the change of com-

[1] J. H. L. Vogt, "Über anchi-monomineralische und anchi-eutektische Eruptivgesteine," *Vid. Selsk. Skr.* I, No. 10 (1908), pp. 24–25.

[2] Vogt, *op. cit.*, p. 41.

position that ensues as the temperature falls. Thus, though the earlier crystals of plagioclase are basic bytownite, they are, in nearly all cases, gradually made over into labradorite by the liquid in which they remain suspended. In the meantime the liquid has suffered impoverishment in ferromagnesian constituents and eventually becomes decisively lighter than the plagioclase crystals. Then and then only, as a rule, does subsidence of plagioclase crystals become an important factor, and masses of anorthosite, anorthosite-gabbro, etc., are formed according to the degree of concentration of crystals. It is to be noted that this lighter liquid from which the labradorite crystals accumulate is now, of course, no longer gabbroic, but, as a result of removal of femic constituents and plagioclase, it approaches syenitic composition, and with continuation of the process actually attains the composition of syenite or granite. In the ideal case in which the process had free scope the resultant mass would be stratified, and would consist of syenite-granite, anorthosite, and pyroxenite in descending order with, in some cases, peridotites at the base. Of all these the only type that was ever liquid as such would be the syenite-granite, though liquids of every composition intermediate between that of the original gabbro and the syenite would be concerned in the process and might occur as chilled borders or in satellitic bodies. The anorthosites should be intimately related to gabbro, therefore, but as intimately related to syenite also, which might occur as interstitial material of late crystallization in some of the phases. By increase of this interstitial material gradual transition into syenite might occur.

Intimate field association of anorthosite with gabbro and with syenite is a fact that no one will question. Some have emphasized its relation to gabbro and some that to syenite, but the emphasis is due as much to the personal element and to the kind of exposures in any particular area as to any fundamental difference between the anorthosites of one area and of another. One would expect, to be sure, that the andesine-labradorite phase of an anorthosite mass would be the more intimately related to syenite, and the labradorite-bytownite phase to gabbro.

Quantitative considerations.—We can perhaps form a better idea of the quantitative relations involved in the process of collection of

crystals if we examine the crystallization of mixtures of the system —diopside, anorthite, albite—not because proportions will be the same, but because they will be rather of the same order in the natural system and will aid us in deciding whether the process is a reasonable method of producing anorthosites as we find them.

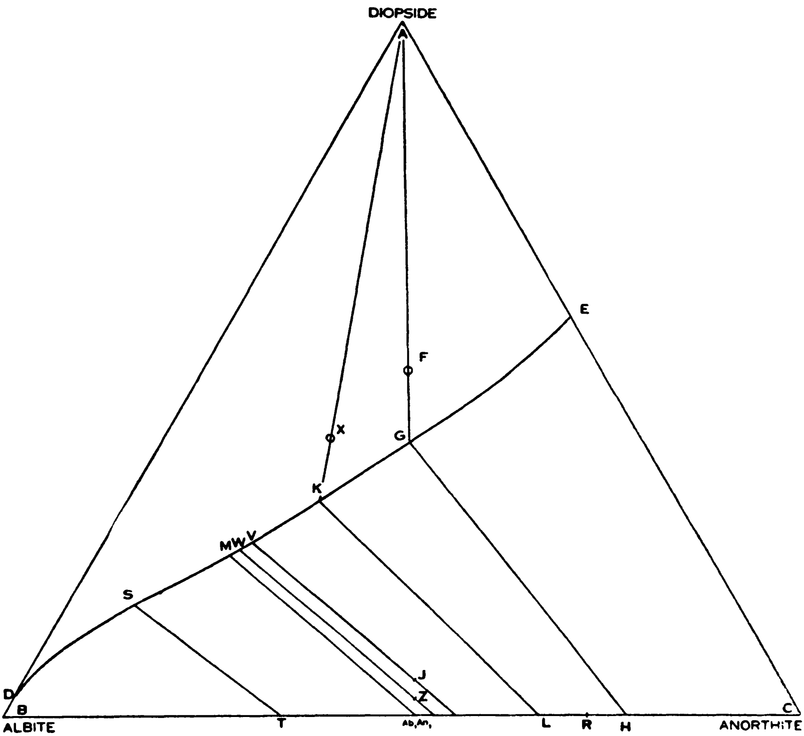

FIG. 1.—Diagram of crystallization in plagioclase-diopside melts

A liquid of composition *F* (Fig. 1), which contains 50 per cent diopside and 50 per cent labradorite (Ab_1An_1), begins to crystallize at 1275°, diopside separating first. As the temperature falls the composition of the liquid changes from *F* along *AFG* (directly away from diopside), and when the temperature 1235° is reached the mass consists of 17 per cent diopside crystals and 83 per cent liquid of composition *G*. At this temperature bytownite of composition *H* (approximately Ab_1An_4) begins to crystallize and the composition

of the liquid changes along the boundary curve *DE* toward *D*. Both diopside and plagioclase continue to separate, and the plagioclase crystals, not only those separating at any instant, but also those which had formerly separated, continually change in composition, becoming richer in albite. At 1220° the whole mass is made up of 37 per cent diopside crystals, 25 per cent labradorite crystals of composition *L* (Ab_1An_2), and 38 per cent liquid of composition *K*. As the temperature falls still lower the liquid gradually decreases in amount and continually changes in composition until at 1200° it is all used up, the last minute quantity having the composition *M*. In the meantime diopside and plagioclase crystals have been separating, and the plagioclase has been changing continuously in composition until at 1200°, when the last of the liquid disappears, the composition of the feldspar is Ab_1An_1. The whole mass now consists of 50 per cent diopside and 50 per cent Ab_1An_1.

Crystallization takes place according to the foregoing outline if no sinking of crystals occurs. If diopside crystals sink, no effect on the composition of the liquid results. We should have then at 1220° a mass in which the diopside crystals were of increasing concentration toward the bottom, and in which a certain upper portion was free from diopside crystals, consisting of 60 per cent of liquid of composition *K* and 40 per cent labradorite crystals of composition *L* (Ab_1An_2). Let us imagine that at this stage appreciable sinking of plagioclase crystals begins, and that it increases in importance as the liquid changes toward *M*, and therefore becomes lighter. It is necessary to imagine also that the plagioclase crystals sink very slowly, and are outstripped by the heavy diopside crystals which are forming simultaneously and which increase in size more rapidly since the liquid is becoming relatively impoverished in diopside. It seems possible, then, that, locally at least, plagioclase crystals might accumulate in a mass free from diopside crystals and containing only a little interstitial liquid whose composition would lie between *K* and *M*. If the mass had 20 per cent interstitial liquid of composition *V* and 80 per cent crystals slightly more calcic than Ab_1An_1, the final rock formed on solidification of the interstitial liquid would consist of 95 per cent Ab_1An_1 and 5 per cent

diopside (J). If the mass had only 10 per cent interstitial liquid of composition W and 90 per cent crystals slightly more calcic than Ab_1An_1, the final rock would consist of 98 per cent Ab_1An_1 and 2 per cent diopside (Z). This degree of concentration of plagioclase is ample for the production of nearly all anorthosites, and is more than sufficient for most of them. To understand the formation of anorthosites of extreme purity it is necessary to follow what has been happening to the liquid in the meantime, that is, to that part of the liquid from which crystals have subsided. Instead of becoming completely crystalline when the composition M is attained, it continues to change its composition toward S and may go even beyond S, that is, it becomes very rich in albite (haplo-syenitic)[1] and the diopside becomes a vanishing quantity. Now it can be considered that locally the interstitial liquid occurring between the plagioclase crystals was of this type, which it might be if the rate of interchange of material did not quite keep up to equilibrium requirements, a very likely possibility. On complete solidification of such a mass anorthosite of extreme purity would result. This would be more likely to give a rock made up of acid labradorite or even of andesine-labradorite. It is because plagioclase crystals may accumulate, under certain circumstances, in a liquid which is itself nearly pure plagioclase (though very different from the crystals in composition) that we can get plagioclase rocks of such extreme purity.[2] For the case of natural rocks the interstitial liquid is enriched, not merely in albite, but also in orthoclase and to some extent in quartz. In those anorthosites that run very low in bisilicates we therefore commonly find 5 per cent or more orthoclase, and occasionally some quartz.

In the foregoing the writer has done his best to picture a process whereby plagioclase crystals may accumulate in sufficient force to give a mass of anorthosite. Unquestionably there are some difficulties, the gravest being that connected with the nearly complete sorting of plagioclase and pyroxene, whose periods of crystal-

[1] N. L. Bowen, "The Crystallization of Haplobasaltic, Haplodioritic and Related Magmas," *Am. Jour. Sci.* (4), XL (1915), 161.

[2] Another possible method of obtaining extreme monomineralic composition is suggested later (p. 238).

lization are in large part contemporaneous. If one could assume that plagioclase follows pyroxene in the crystallization of gabbro, as some geologists appear to do, the sorting would be a simple matter, but chemical considerations will not permit such an assumption. Yet the difficulties do not seem insurmountable, especially in comparison with those connected with other processes. Diffusion is hopelessly incompetent even if it is assumed that its tendency is in the proper direction. Liquid immiscibility, whose operation in the case of silicates has nothing to support it, would certainly not tend to produce pure liquids in any case, but only to produce liquids of contrasted composition, all being, nevertheless, mutual solutions of minerals. Added to these is the temperature objection to which reference was made on an earlier page, and still others might be mentioned. On the other hand, it does seem reasonably probable that a mass of gabbroid magma might cool sufficiently slowly to permit the necessary amount of sorting of crystals especially if it was a large mass, or if it was very deeply buried.

CHARACTERISTICS OF ANORTHOSITE CONSEQUENT UPON THE SUPPOSED METHOD OF FORMATION

It must be admitted, however, that opinion as to whether the process can take place is not a very decisive matter. More important is the deduction of its consequences followed by a survey of the characteristics of anorthosites in order to determine to what extent they agree with the requirements. If anorthosites are generated only by the accumulation of crystals, then the more nearly a rock mass approaches an exclusively plagioclase composition, the more nearly it should have approached the completely solid condition when that composition was attained. In discussing artificial melts we have seen that if we have a portion with 80 per cent plagioclase crystals and 20 per cent interstitial liquid it would, on crystallization, have 95 per cent plagioclase and 5 per cent diopside. In other words, a rock containing only 5 per cent diopside could have had, after that total composition had been attained by the process we are considering, not more than 20 per cent liquid. A rock containing 10 per cent diopside could have had a maximum of 35 per cent liquid, and one containing only 2 per cent diopside

could have had not more than 10 per cent liquid. For natural melts the figures would not be the same, and the probability is that the amount of liquid would be relatively somewhat larger on account of the presence of orthoclase in the liquid. Assuming the figures to be approximately the same, it seems necessary to believe that a rock containing 95 per cent or more plagioclase, if it is true that it is formed by the method outlined, should exhibit certain characteristics that set it apart from such a rock as a granite, which, as we know well enough, often occurs in the completely molten condition. When the plagioclase rock is formed *in situ*, it need exhibit no features differentiating it from other igneous rocks except perhaps a marked coarseness of grain. Such a body, while still containing nearly its maximum of about 20 per cent interstitial liquid, might be moved *en masse*, though probably not far, from the position of its original formation, but this movement would be accompanied by the development of protoclastic structure, especially about the margins. Since all crystalline igneous rocks pass through a stage at which they are 80 per cent crystalline, all are subject to the possibility of the development of similar structures under parallel conditions. The plagioclase rock differs only in that it cannot be moved without developing this structure, since if moved when containing more than 20 per cent liquid the mass moved has not yet attained the requisite degree of concentration of plagioclase crystals. Protoclastic structure and granulation should therefore be perfectly general features of all moved anorthosite masses and very common features of all anorthosites.

When we come down to the movement of such material in small masses, it seems impossible that it would be capable of being injected into small openings in cold country rock—in other words, that it would form no small dikes in such rocks, though it might occur as dikelike masses in consanguineous igneous types, being injected into them at a time when they themselves were not completely crystalline. Such material should, moreover, be incapable of occurring as effusive flows.

For the purposes of the foregoing discussion a mass containing 20 per cent interstitial liquid has been arbitrarily chosen. It is a matter of opinion how much liquid a mass must have in order to

be injected as small dikes. If it is considered that about 50 per cent liquid is necessary, then only anorthosite or, better, anorthosite-gabbro, with about 85 per cent plagioclase could occur as small dikes. If somewhat less than 50 per cent liquid is necessary, then a rock somewhat richer in plagioclase could occur in that manner. In the case of effusive masses, if it is considered that more than 50 per cent liquid is normally requisite for their formation, only anorthosites with less than 85 per cent plagioclase could occur as effusives.

A study of the literature of anorthosites from various localities seems to show that, in so far as published descriptions are concerned, anorthosites do have substantially the characters outlined in the foregoing discussion, which is based on the hypothesis that they are accumulated masses of plagioclase crystals. Still the idea is rather novel, and probably no one had such a hypothesis in mind when examining anorthosites, so that, while many observations bearing directly on the problem are recorded, one might readily believe that perhaps many others equally pertinent escaped record. For this reason the writer spent a few weeks in the Adirondack area and in the Morin area of anorthosites, becoming acquainted at first hand with the relations there found. Attention was confined almost entirely to parts already mapped in detail so that a maximum could be seen in the limited time. The facts bearing on the origin of anorthosites in these areas will be stated principally as recorded by others, and only to a very limited extent supplemented by this brief personal experience. It is desired to express thanks to Professors Kemp, Cushing, and Adams and to Mr. Dresser for interest taken and for furtherance of the work in various ways.

THE ADIRONDACK ANORTHOSITE

General relations.—The anorthosite of the Adirondacks occurs principally as a single great area, for the most part in the heart of the mountains and making up its highest peaks, though extending eastward to the lower country in the vicinity of Lake Champlain. The mass occupies an area approximating 1,200 square miles, the principal constituent of the rock throughout this area being plagioclase. Large exposures may be made up almost exclusively

of plagioclase, while other exposures, perhaps equally general and widespread, would average nearly 10 per cent bisilicates. This latter type seems to prevail even in the heart of the area being represented in most of the exposures of the Keene Valley, while the bare ledges of the summit of Mt. Marcy average probably more than 5 per cent bisilicates. Toward its borders, too, the anorthosite commonly passes into anorthosite-gabbro and gabbro. Nevertheless, the mass as a whole is aptly described as consisting of "little else than feldspar which is generally a blue labradorite."[1] If this great mass, whose volume is to be measured in thousands of cubic miles, was ever molten as such, it is remarkable that none of the many investigators who have studied the area have found a single dike consisting of nearly pure plagioclase in the surrounding rocks. The evidence of the intrusive nature of anorthosite in its more typical development depends on the occurrence of Grenville inclusions in it. To be sure, the anorthosite is nearly always immediately surrounded by a younger rock, the syenite, but in several localities the invading power of certain phases of the anorthosite mass is well shown. Anorthosite-gabbro invades the Grenville and associated older gneisses in places, and occurs as outlying masses upward of 20 miles distant from the main anorthosite mass. As soon, then, as the bisilicates mount to 20 or 25 per cent there is no lack of evidence of the power of the mixture to penetrate into openings in the surrounding rocks. The great mass of the anorthosite itself contains much fewer bisilicates, yet in spite of the overwhelming volume of such material it is entirely unrepresented as dikes and small intrusions. It seems to be a reasonable conclusion that this material was incapable of being injected into the older rocks.

Intimate relation of syenite and anorthosite.—The anorthosite core of the Adirondack igneous mass is surrounded practically everywhere by the syenite-granite series with which are associated numerous areas of Grenville sediments and perhaps older granite gneiss. There has been a considerable tendency to consider the syenite-granite as an igneous unit and anorthosite as a separate unit. This tendency has been emphasized perhaps by the fact

[1] D. H. Newland, *N.Y. State Museum Bull. 119*, 1908, p. 17.

that in one locality, in the vicinity of Long Lake, Cushing was able to demonstrate that the syenite is younger than the anorthosite. Yet even Cushing states: "The syenite and anorthosite seem surely derivatives from the same parent magma and of no great difference in age."[1] This aspect of the anorthosite, i.e., its intimate connection with the syenite, is emphasized in the area as a whole, where, in spite of fairly good exposures, only one other locality showing the intrusive relation of syenite to anorthosite has been found, but where, on the other hand, types intermediate between the two are rather commonly found. This feature of Adirondack igneous geology has not been studied in detail except, apparently, at the one locality in the Long Lake quadrangle, though it appears to deserve such study since it marks the great similarity between the Adirondack anorthosites and others, the Norwegian and Volhynian occurrences, for example. In the writer's limited experience it was found that the change from anorthosite to syenite was heralded by the appearance of inclusions of potash feldspar in the plagioclase. The inclusions are small patches, uniformly oriented and constituting therefore an antiperthite.[2] These inclusions often show a rather peculiar feature which, so far as the writer is aware, has not been noted elsewhere. Surrounding some of them and corresponding in general though not in detail with the outline of the inclusion is an area of plagioclase differing from the crystal as a whole. Its outline is usually sufficiently sharp to make it possible to determine that it has a slightly higher refractive index than the rest of the plagioclase, besides a different position of extinction which makes it a rather conspicuous feature. An extremely fine twinning, not shown by the main body of the plagioclase crystal, can usually be seen with high magnification. A suggested explanation of these features is that the material of the microcline inclusions was originally in solid solution in the plagioclase and that on separating from solid solution it left the plagioclase poorer in potash feldspar, and therefore of higher refraction than the general body of the crystal more remote from the inclusions. But the rims about the inclusions usually have not much greater mass than the inclusions

[1] *Bull. Geol. Soc. Am.*, XVIII (1907), 485.

[2] F. E. Suess, *Jahrb. K. K. geol. Reichsanst.*, LIV (1904), 417–30.

themselves, and it would be necessary for the surrounding plagioclase to have contained originally nearly one-half potash feldspar, which it certainly did not. It seems more likely that the potash feldspar, though occurring as definite inclusions, was, nevertheless, formed from the portion which remained liquid last and was introduced into the plagioclase by a sort of replacement, the change in the plagioclase aureole being an effect going hand in hand with this replacement.

With the microcline inclusions some interstitial microcline generally makes its appearance, and this may increase in amount until it becomes an important constituent of the rock. In such a specimen the plagioclase is usually andesine rather than labradorite, though the large blue labradorites typical of the anorthosites often occur as phenocryst-like individuals. The rock is definitely intermediate between anorthosite and syenite, though the microcline, in the few slides examined, has not as marked a tendency to be perthitic as it has in the typical syenite. One sees these intermediate types in some of the exposures about the shores of Lake Placid. There is apparently a transition between some of the rocks mapped as gneiss (syenite-granite) and those mapped as anorthosite in that vicinity.[1] Similar intermediate types are found in the vicinity of Elizabethtown, and as a whole they seem to be closely analogous to the perthitophyres of Volhynia as described by Chrustschoff,[2] and to the Norwegian monzonites described by Kolderup.[3]

An interpretation of the structural relations of syenite and anorthosite.—While the anorthosite and syenite are evidently closely related and connected by transitional types, they are usually very distinctive. There is one aspect of their field relations in which they are strongly contrasted and with which the writer was impressed in the field. In the great area of syenite-granite that surrounds the anorthosite core, areas of Grenville are exceedingly numerous. In many of the mapped quadrangles it has been neces-

[1] Map accompanying report by Kemp, "Geology of the Lake Placid Region," *N.Y. State Museum Bull. 21*, 1898. Since the above was written the writer has been informed by Professor William J. Miller that, while the transitional relation is shown, the syenite also sends dikes into the anorthosite.

[2] *Tschermak's Min. Petr. Mitt.*, 9 (1888), p. 470.

[3] *Bergens Museums Aarbog*, No. V (1896), p. 86.

sary to use a color to represent a mixture of Grenville and syenite that defies separate mapping. Now the manner of occurrence of the Grenville when found in considerable areas is commonly as a roof lapping over the syenite and showing only comparatively moderate dips. One sees this in typical form on the shores of Lake Champlain immediately north of Port Henry, and Miller has recently described this relation in widely scattered Adirondack localities, the large-scale example in the Blue Mountain quadrangle being of special interest.[1] Syenite and Grenville in this relation are almost constant companions.

The anorthosite areas, on the other hand, are very different. It could be said with little exaggeration that on passing the borders of the anorthosite core one encounters only anorthosite. It is true that inclusions of Grenville have been found, enough to prove the intrusive nature of the anorthosite, but these appear to be small completely inclosed blocks and do not suggest actual roof remnants. In spite of their occasional occurrence the contrast between the syenite and anorthosite areas is very striking. One has but to glance at the maps of such areas as the Paradox Lake and Long Lake quadrangles to be convinced of it. Not only is the anorthosite unbroken by areas of Grenville, especially away from the margins, but it is likewise practically free from protrusions of the syenite, although the syenite is, as we have seen, in part at least, a later rock. If one pictures the syenite and the anorthosite as conventional batholiths, some difficulty is experienced in accounting for the foregoing facts. It is necessary to imagine an early intrusion of a huge plug of anorthosite followed by an intrusion of syenite which took the form of a hollow cylinder circumscribing it and invading it only peripherally. All of this must take place without throwing the Grenville series into appressed folds, indeed, without very significant folding of any kind. It is then necessary to imagine that erosion removed every vestige of a roof from the small interior anorthosite area, and left great stretches of it throughout the broad syenite-granite belt that surrounds it.

All of this is perhaps possible, but at the same time seems highly improbable. On the other hand, if one pictures the Adirondack

[1] William J. Miller, *Jour. Geol.*, XXIV (1916), 591.

complex as essentially a sheetlike mass with syenite overlying anorthosite, the facts of Adirondack igneous geology seem to arrange themselves more rationally. On this supposition one would expect to find areas of the Grenville roof covering the syenite in places and to find it relatively little disturbed. In the interior and

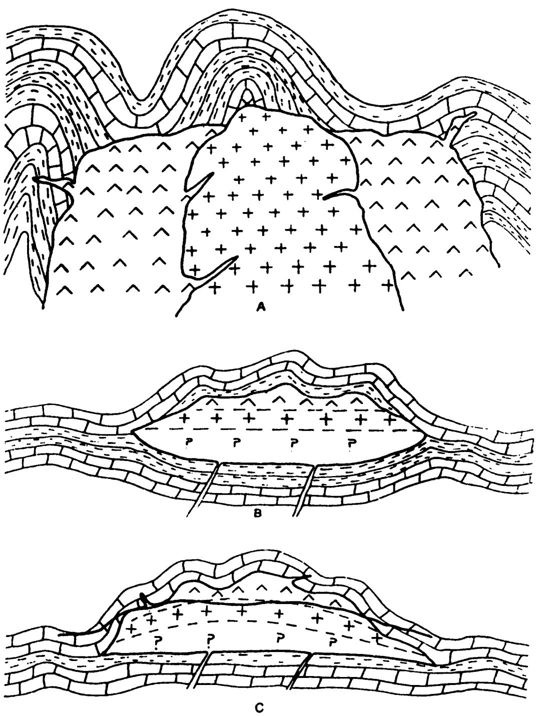

FIG. 2.—A. Adirondack complex interpreted as batholitic. +Anorthosite, ^ Syenite
B. Adirondack complex interpreted as laccolithic (undisturbed)
C. Same as B after disturbance. Heavy line indicates erosion surface

eastern region of maximum uplift one would expect to find the deeper-seated anorthosite laid bare and to find it free from areas of the roof since it was for the most part separated from the roof by a layer of syenite. (In Fig. 2 the alternative interpretations of the Adirondack complex are presented.)

On this supposition of the origin of syenite and anorthosite by gravitative differentiation of a sheetlike mass it is by no means

necessary that syenite and anorthosite should always grade imperceptibly the one into the other. The Adirondack area is one of considerable disturbance. It no doubt suffered some disturbance at the time of the intrusion of these igneous masses, and it has unquestionably been much faulted since their consolidation. Is it reasonable to suppose that the region necessarily stood stock-still during the long period required for the consolidation of these igneous masses? It is, in fact, likely that faulting took place during this period as well, and if it occurred at a time when the anorthosite was completely crystallized but the syenite still molten then it is quite possible that syenite might thus be brought laterally against, and acquire an intrusive relation to, anorthosite. The fact that syenite invades anorthosite locally need not therefore be fatal to the conception of gravitative differentiation of these two types, nor does it necessarily indicate the order of their arrival from the depths. A diagrammatic simplicity is not to be expected, but the broader relations, including the substantial freedom of the whole interior of the anorthosite area from protrusions of syenite, seem to give a distinct preference to their arrangement substantially as layers with the syenite above as outlined in the foregoing.[1]

The writer's leaning toward differentiation practically in place as the explanation of the variation of many batholiths has been criticized publicly by Harker,[2] and by others in private correspondence. It is apparently believed that when one rock invades another the relation necessarily means that the invading rock arrived from a deep-seated magma basin subsequent to the other. This may be quite true, as a rule, but there is little evidence in most cases that adequate consideration has been given to the alternative view of differentiation practically in place with only relatively minor disturbance during the magmatic period. The petrologist should be reluctant to reject this possibility without fair trial, for he destroys some of the hope of solving the problems of igneous

[1] A few small patches of syenite have been found within the anorthosite area. If these are regarded as having been pushed up from below as pipes, it is rather remarkable that in no instance has their intrusive nature been demonstrated. On the other hand, if they are remnants of an overlying syenite, they might well lack a definite intrusive character.

[2] *Jour. Geol.*, XXIV (1916), 554.

geology by thrusting the locus of differentiation ever backward into unseen depths. The Adirondack intrusives would, it is felt, be interpreted by many in the conventional manner, and for this reason some pains have been taken to present the alternative view.

Daly regards the Adirondack anorthosite-syenite complex as probably a laccolith. According to his views anorthosites are formed in laccoliths because those masses suffer little contamination from wall-rock material and anorthosite is a pure differentiate of gabbro magma. A certain amount of assimilation of wall rock can occur, however, without eliminating the possibility of the formation of anorthosite, and under such circumstances the syntectic magma differentiates in such a manner that syenite is formed. In batholiths, on the contrary, whose emplacement takes place by stoping, the consequent assimilation has so important an effect on the gabbroic magma that no anorthosite is formed, according to Daly. The writer's interpretation of the Adirondack complex as a stratified, sheetlike mass with a lower layer of anorthosite and an upper layer of syenite intimately associated with the Grenville sediments is therefore in striking agreement with Daly's conception. However, a consideration of crystallizing magmas in the light of experimental study compels the writer to believe that there would exist in association with the anorthosite a mass of syenite, even if the invaded rocks were of infinitely refractory and inert materials. The mass of syenite was probably augmented by assimilation of foreign rocks, but that is a different matter. Apparently this opinion is in accord with the conclusions of those best acquainted with the Adirondack rocks in the field who, while demonstrating that assimilation takes place, consider it rather as an incident than as a fundamental factor controlling the genesis of rock types. And, again, the writer's interpretation of the igneous mass as sheetlike is offered merely because of the difficulty of picturing the general relations otherwise. Indeed, it is not considered that the Adirondack batholith or laccolith or whatever it may be called, is exceptional in this respect. Most batholiths are regarded by the writer as just such masses. Consequently it is believed that the shape of the intrusive is not the determining factor in the formation of

anorthosite. It is rather a balance between density, rate of cooling, and viscosity such that the necessary amount of sorting of crystals occurs.

The writer must confess an inability to state precisely the reason why the species presented in an igneous sequence at one locality may be different from those at another. It is nevertheless believed that it is unnecessary that the original magmas need have been different, or even that the manner of differentiation need have varied. The results seem to be possible if there was a variation in the extent to which separation of crystals from liquid and also sorting of individual minerals were able to take place. Variations in these factors depend on physical conditions which have, however, their chemical consequences, for the removal or non-removal of a crystal has each a perfectly definite effect on the future course of the liquid.

In one sequence, which is well shown in the pre-Cambrian of Ontario and in certain British intrusives, there is practically only gabbro and granite with little that could be described as intermediate. Apparently this is especially likely to be true of masses of moderate size. In somewhat larger masses ultrabasic rock may make its appearance as one of the members with occasionally some anorthosite. Usually for the formation of anorthosite a very large mass is necessary, and possibly also a deep-seated mass. On the other hand, for the formation of those sequences that emphasize intermediate types such as diorite, quartz diorite, and granodiorite the indications are that very large masses are necessary, but that they should probably occur at moderate depths. There is nothing here in the way of hard and fast rules, but there do seem to be fairly definite tendencies. All of these are reasonably to be considered the result of differences of the physical conditions under which cooling took place.

THE MORIN ANORTHOSITE

General features.—The Morin anorthosite area of Canada is in many respects very like the Adirondack area. It lies near the edge of the great pre-Cambrian shield where it is overlapped by Paleozoic rocks. It covers a territory of about 1,000 square miles which, while not as mountainous as the Adirondacks, is nevertheless quite

rugged, many of the important elevations of the Laurentian Mountains of that region lying within the boundaries of the anorthosite mass. As with the Adirondack Mountains, the Laurentian Mountains have suffered glaciation and lakes abound, with the result that even in the matter of popularity as a summer resort the two regions are alike, the Laurentian region drawing a plentiful supply of tourists on account of its proximity to the Canadian metropolis. Coming to the more fundamental matters of geologic structure and petrography we find again a remarkable degree of similarity to which attention is directed in the sequel.

An area of more than 3,000 square miles comprising the Morin anorthosite was mapped nearly thirty years ago by F. D. Adams, and a map published on a scale of four miles to one inch.[1] The map is therefore not as detailed and does not form as useful a guide for one who would see a great deal in limited time as do the quadrangle maps of the New York State Museum, which are the result of the labors of a number of workers. On the other hand, the text of the report is full of minute descriptions of localities, and a brief visit was paid to some of these in order to become familiar with them at first hand.

Relation of anorthosite to the surrounding rocks.—The Morin anorthosite occurs, as does that in the Adirondacks, principally as a single, great intrusive mass. There is, however, a greater number of small outlying masses that give the area a somewhat greater interest with reference to the problem of the origin of anorthosite. The associated rocks are practically identical with those in the Adirondacks, consisting of igneous gneisses largely of salic composition and of sediments of the Grenville series. Of all these Adams concluded that the anorthosite was the youngest, a relation which he appears to have considered a general one for the Canadian anorthosites including the great Saguenay mass. Recent study of the Saguenay area has shown, however, that there are associated with the anorthosite certain more salic types, possibly consanguineous with it, but of somewhat later age,[2] the whole being appar-

[1] "Geology of a Portion of the Laurentian Area North of the Island of Montreal," *Geol. Surv. Can. Ann. Rept.*, Vol. VII, Part J, 1896.

[2] Personal communication from Mr. Dresser.

ently a counterpart of the anorthosite-syenite association in the Adirondacks.

While the writer has nothing very definite to offer concerning a similar association in the Morin area, certain indications were found tending to show that detailed study might definitely bring out its existence there. In the vicinity of Piedmont and extending southeastward beyond Shawbridge the gneiss which here forms the southern boundary of the anorthosite mass is a rather fine-grained greenish rock looking very similar to the syenite of the Adirondacks. Specimens of this taken at various distances from the borders of the anorthosite show that it varies considerably. In all cases the rock is composed principally of plagioclase but, on receding from the border of the anorthosite, orthoclase continually increases in importance. There is apparently a perfect transition from anorthosite toward syenite, though in none of the specimens collected had the change gone to completion, that is, none of the specimens could be called typical syenite. In one specimen, however, orthoclase made up about 30 per cent of the rock, and was accompanied by some quartz, so that probably the change would not have to be followed much farther to afford typical syenite.[1] On account of this transitional relation it is very difficult, at least where seen by the writer, to fix a boundary between anorthosite and gneiss. Specimens that are apparently typical anorthosite and taken well within the boundary of the mass as mapped by Adams, are found to be like those types of anorthosite of the Adirondacks which show the beginning of transition to syenite in that the plagioclase contains orthoclase inclusions. Specimens from the cliffs north of Piedmont station show the orthoclase in streaks forming an antiperthite much richer in orthoclase than any seen in Adirondack specimens.[2] Even specimens taken four miles within the border of the anorthosite, in the village of Ste. Adèle, show abundant orthoclase inclusions in the plagioclase.

[1] Professor Adams informed the writer in conversation that intermediate monzonite types analogous to the Norwegian types of Kolderup occur in the region, so that, while they are not described at length in his report, he undoubtedly recognized such types.

[2] In none of the Canadian specimens was there seen any peculiar zone of plagioclase surrounding the orthoclase inclusions as described from the Adirondack localities.

In the vicinity of Piedmont occasional dikelets are seen cutting the anorthosite, which are found to consist principally of microperthite with some quartz and an unusually large amount of magnetite, a composition that suggests a syenitic source. Taken all in all the evidence favors the possibility that we have in the Morin area syenite and anorthosite related in the same manner as in the Adirondacks, in part transitional into each other, but the syenite of somewhat later consolidation. Even in the matter of the occurrence of a certain aberrant type the two regions show a further similarity. In the vicinity of Elizabethtown, New York, there is a peculiar dark rock resembling a basic syenite, but containing phenocrysts of the blue labradorite which is described by Kemp as the Woolen Mill type.[1] This rock is duplicated in both megascopic appearance and microscopic characters in exposures in the streets of the village of St. Jérome, Quebec. It is apparently intimately related to both syenite and anorthosite.

Concerning the structural relations of syenite-granite and anorthosite it is impossible to say anything definite, since syenite that may be regarded as probably related to the anorthosite has not been delimited. About twenty miles east of the anorthosite mass, syenite-granite makes its appearance from beneath the flat-lying gneiss of the surrounding country. Adams considers that the syenite is much more widespread, the gneiss of the surrounding area forming merely a relatively thin and little disturbed roof over it. If the anorthosite is, as in the Adirondacks, a deep-seated portion of the same igneous complex, then in order to bring the anorthosite and the roof gneiss into lateral juxtaposition a considerable movement would be necessary, and it is found that, after passing westward over a twenty-mile stretch of little disturbance, the gneiss is then, on approaching the anorthosite, thrown into sharp folds.[2] Moreover, we find on passing within the border of the anorthosite mass that the typical roof gneiss with its occasional bands of limestone is absolutely lacking, a fact that suggests that the roof gneiss was nowhere superposed directly upon the anortho-

[1] "Geology of the Elizabethtown and Port Henry Quadrangles," *N.Y. State Museum Bull. 138*, 1910, p. 35.

[2] Adams, *op. cit.*, pp. 11 and 12.

site. Not impossibly, then, there may be in the Morin area a stratified mass, made up of syenite above and anorthosite below, with general relations similar to those we have imagined to exist in the Adirondacks.

Lack of mineralizers in the Morin anorthosite.—On an earlier page it was pointed out that there is in anorthosite no supply of minerals other than plagioclase adequate to produce significant lowering of the melting temperature of the plagioclase. Anorthosite could exist as magma, therefore, only at very high temperatures unless there was present a proportion of volatile components sufficient to produce great lowering. Adam's work on the Morin anorthosite appears to give a definite negative answer to this possibility. The minerals normal to the anorthosite are those commonly believed to form from relatively anhydrous melts. The ferromagnesian material appears typically as pyroxene, not as hornblende or mica. There is little if any tendency for the pyroxene to be made over into hornblende or mica even in the very latest stages of crystallization when the volatile components would reach their maximum concentration. Even intense shearing of the rock, which took place partly during this latest stage of crystallization and partly immediately subsequent thereto, had no tendency to develop hornblende and mica from the pyroxene, though under such conditions it is well known to be particularly susceptible to this change if there are mineralizers present in significant quantity.

All of the evidence points to a substantial lack of mineralizers. The Morin anorthosite is in these, as in most respects, typical of the world's anorthosites. We are therefore impelled toward the belief that, inasmuch as anorthosites show no definite high-temperature characters, they are preferably to be considered as never having been molten as such.

Anorthosites as small intrusions.—In considering the physical condition of the anorthosite as bearing on this question of its origin it is perhaps well to recall the circumstances under which Adams' investigation was undertaken. Prior thereto there had been a common tendency to believe that all banded rocks were of sedimentary origin, and since the anorthosite is often markedly banded it had been regarded as a member of the sedimentary series with

which it is associated. Adams entered the field as the champion of the newer conception that many banded gneisses are of igneous origin, and that of these the anorthosite was a prominent representative. Under such circumstances it cannot be questioned that any geologist would search diligently for dikes and tongues of anorthosite running out into the surrounding rocks, and that having found them he would not fail to record them. Yet one will search Adams' report in vain for a single instance of such a dike. The wording of the one statement which is an apparent exception serves only to emphasize the truth of the above. The anorthosite mass is described as "sending *an apophysis*" into the surrounding gneiss.[1] The apophysis referred to is a great armlike extension five miles wide. Attention is directed to this lack of dikes in order to emphasize that here we have an intrusive of a peculiar character, not to call in question the interpretation of the anorthosite as an intrusive. Of that there can be no question. Dikes intimately related to the anorthosite do occur, but they serve to emphasize the more that there are none consisting almost entirely of plagioclase, though there is mile upon mile of such rock within the main body of anorthosite. It seems reasonable to conclude, therefore, from the evidence in the Morin area, that a rock consisting almost entirely of plagioclase is incapable of being injected as dikes. The reason for this is to be found, it is believed, in the manner of its origin, a mass of anorthosite being merely a collected mass of plagioclase crystals.

There are, as has been stated, several small outlying masses of anorthosite besides the great central mass. These are listed and described in detail by Adams. Some of them were visited by the writer, but nothing need be added, indeed nothing can be added, to Adams' statements, which are quite explicit with reference to the point that it is desired to emphasize. In discussing the anorthosite of the outlying masses in general he states: "It is perhaps on the whole richer in iron magnesia constituents and often contains minerals such as hornblende and biotite."[2] Statements of like import are made in discussing the bands severally. Of the Kildare

[1] *Op. cit.*, p. 116. Italics are the writer's. [2] *Ibid.*, p. 117.

bands he says: "The rock is on the whole richer in bisilicates than the Morin anorthosite, approaching more nearly a normal gabbro or norite in composition."[1] Practically the same statement is made of the Cathcart bands;[2] and again of the Brandon bands he says: "Like most of the small anorthosite bands described in this report, these from the township of Brandon are usually richer in bisilicates than a true anorthosite should be."[3]

Apparently, then, these outlying bands always vary from typical anorthosite, usually toward gabbro, but in one or two instances perhaps the variation is toward syenite-granite, as suggested by a content of hornblende and biotite. The bands are by no means inconsiderable bodies, usually having a width of upward of half a mile or more and a length of several miles. Even masses of this size are apparently never made up of nearly pure plagioclase rock, a fact that accords with the belief that a fair proportion of other minerals is necessary before anorthosite acquires appreciable invading power in masses of limited size.[4]

CONSIDERATION OF ANORTHOSITES IN GENERAL

The agreement of the two most completely described areas of anorthosite on the North American continent with the consequences of the hypothesis of the origin of anorthosite is apparently rather good. The Norwegian and the Russian areas are equally significant, but no attempt will be made to discuss them in detail. Reference will be made, however, to the schematic presentation of differentiation given by Kolderup, which is based entirely on field evidence, and of which a copy is presented below. Attention is called to the central position of the norite with its anchi-monomineralic basic differentiates and its more complex acid derivatives. These are, it is believed, the accumulations of sorted crystals on the one hand, and the residual liquids on the other.

[1] *Ibid.*, p. 122. [2] *Ibid.*, p. 124. [3] *Ibid.*, p. 126.

[4] A dike of anorthosite in the Cripple Creek country, to which the writer's attention was called by Professor Graton as an apparent exception, is described as containing biotite and quartz. It evidently varies toward granite, and its occurrence as a dike might reasonably be expected.

KOLDERUP'S REPRESENTATION OF DIFFERENTIATION IN THE EKERSUND-SOGNDAL ANORTHOSITE AREA

Bronzite granite
|
Adamellite
|
Banatite
|
Monzonite
|
Quartz-norite
|
Gabbro-norite—Norite—Anorthosite-norite—Anorthosite
|
Bronzitite—Norite-bronzitite
|
Ilmenite-norite
|
Ilmenitite

Kolderup's anorthosites become more basic and schistose toward their borders and their contact relations are obscure. One cannot be sure from his text whether there are small dikes of anorthosite in the surrounding rocks or not, but apparently there are not.[1]

Apophyses consisting of 95 per cent basic labradorite and 5 per cent augite cut the Sooke gabbro of Vancouver Island described by Clapp.[2] The anorthosite veins and the gabbro are consanguineous, however, and the former with, say, 20 per cent liquid might have been squeezed into the not completely crystallized gabbro mass, the process involved being then rather different from that occurring in the injection of anorthosite into cold country rock.

Dikes of anorthosite are described as cutting the older rocks in the Rainy Lake region, but one cannot be sure from the description whether the dikes are strictly anorthosite or rather the related anorthosite-gabbro.[3] And so it is with many descriptions. It is profitless, therefore, to pursue the discussion of various anorthosite occurrences further since they were not examined with the questions

[1] "Die Labradorfelse des westlichen Norwegens," *Bergens Museums Aarbog*, No.V (1896), p. 14.

[2] C. H. Clapp, "Southern Vancouver Island," *Geol. Survey Canada Mem. No. 13*, 1912, p. 116.

[3] Since the above was written Professor Coleman has informed me that in so far as he can recall there are no dikes of typical anorthosite.

raised in mind. An individual cannot do more than state the problem and leave its suggested solution to confirmation or refutation at the hands of those acquainted with various anorthosites in the field.

Of anorthosite in general it can be said, however, that no effusive equivalent has hitherto been found anywhere. This must be regarded as a very surprising fact if there were ever masses of molten plagioclase adequate to furnish such great exposures of anorthosite as occur in various parts of the earth. On the other hand, if these anorthosite masses were merely collections of plagioclase crystals effusive anorthosites are scarcely to be regarded as possible.

MONOMINERALIC ROCKS IN GENERAL

Enough has been said incidentally in the foregoing to make it clear that the problem of any monomineralic rock is, in its essentials, the same as the problem of the anorthosites. There are no more promising methods of obtaining pure molten olivine or pyroxene than there are of obtaining molten plagioclase. On the other hand, the collection of crystals to give substantially solid masses of nearly pure olivine or pyroxene does not seem out of the question.

A survey of the domain of igneous geology lends considerable support to the possibility that peridotites and pyroxenites are so generated. In making the test of their occurrence as small dikes we find that this is perhaps the most characteristic manner of occurrence of peridotite, but on closer examination it appears that this fact may be due rather to the elastic nature of the term peridotite, which may be applied to a rock containing considerable plagioclase, pyroxene, hornblende, or mica, or all of these, as well as its olivine. Typical dunite, or nearly pure olivine rock, however, probably does not occur as dikes, if we except, again, its occurrence in such form in closely related and essentially contemporaneous igneous rocks. The same statement may be made of rock types excessively rich in pyroxene. As to the question of their occurrence as effusive types it is found that peridotite has an effusive equivalent in picrite, but picrite is far from being a pure olivine rock. Dunite itself has apparently no effusive equivalent. With the

pyroxenites the case is apparently the same. Limburgite and augitite can scarcely be regarded as monomineralic rocks in the stricter sense of the term, and that is the only sense in which it can be used in testing the hypothesis. The presence of both pyroxene and olivine, of a glassy base and usually of some feldspathoid makes it clear that these effusive pyroxenites do not constitute an exception to the rule that the monomineralic rocks do not have effusive equivalents. Apparently, the facts are in accord, therefore, with the hypothesis that monomineralic rocks are accumulated masses of crystals.[1] Mention may be made again here of Vogt's discovery that the richer a peridotite is in olivine, the richer the olivine is in magnesia, a fact which is readily explained on the assumption that peridotites are made up of accumulated early crystals.

All of the monomineralic rocks often do occur, however, in a manner which has led a very great number of investigators to speak of the magmas of these rocks as freely as of the magmas of any others. This is probably due partly to the fact that the possibility of their origin after the manner here advanced did not occur to the investigators, but whether this was always the case is a question that, again, an individual cannot answer. One of the most remarkable occurrences of anchi-monomineralic rocks, especially pertinent in the present connection, is that described by Harker from the islands west of Scotland. As a result of his minute descriptions an especially favorable opportunity is offered of discussing these rocks in the light of the present conception of the origin of monomineralic rocks. The rocks are intricately banded in such a manner as to lead Harker to suggest the intrusion of a non-uniform magma, implying apparently a non-uniform liquid.[2] A difficulty in the way of accepting this interpretation is that connected with obtaining a non-uniform liquid, especially with

[1] While it has been necessary in applying the foregoing tests to set aside anchi-monomineralic rocks containing a considerable amount of other minerals, it should not be assumed that there is any essential difference in the method of formation. These are merely examples in which accumulation of crystals of one kind has not taken place to quite the same degree and which consequently could have had a considerable amount of interstitial liquid.

[2] "Geology of the Small Isles of Inverness-shire," *Mem. Geol. Survey Scotland*, 1908, p. 74.

such extremes of composition. There is no promising method of doing so. Another difficulty presents itself in the very rapid changes from one type to another. Even granting some method of obtaining a heterogeneous liquid, one encounters the problem of maintaining these sharp contrasts in adjacent liquids, for diffusion, though unquestionably a slow process, would nevertheless accomplish much through moderate distances in the time required for the cooling of such masses. On the other hand, it seems reasonably possible both to obtain and to maintain almost any degree of heterogeneity as a result of the accumulation of crystals. On this assumption it is necessary to imagine the source of the olivine-rich types in a portion of the magma reservoir where olivine crystals had accumulated and of the feldspar-rich types where feldspar crystals had accumulated. These partly crystalline masses were thrust into the position where found. The greater the approach to monomineralic composition, the less liquid there could have been. In accordance with this conception it is found that in the allivalite the feldspar crystals are arranged with their elongation in the direction of flow of the sheets, and that this becomes more marked the richer the rock is in feldspar. In the case of bands consisting almost entirely of one mineral, which should have had very little liquid to lubricate their flow, it is found that characters consequent upon this are developed. Thus the nearly pure feldspar rock is described by Harker as strongly fissile and the pure olivine rock as foliated.[1] Possibly connected with the nearly solid condition of these rocks as injected is the fact that their intrusion apparently involved overthrusting, at least it is intimately connected with a line of overthrusting along which earlier, later, and possibly contemporaneous movements took place.

In correspondence with the unusual conditions of formation and intrusion of these ultra-basic rocks we find them to be scarcely duplicated elsewhere. The Russian ultra-basic rocks described by Duparc and Pearce seem to be their nearest relatives. They show a not dissimilar banding of closely related types and possibly may be explained in a like manner. The peridotite dikes are described as

[1] *Op. cit.*, pp. 72 and 87.

"parfois légèrement schisteux."[1] It may be noted at this point, also, that an augitite associated with the perfectly massive alkaline types of the Ice River district, British Columbia, is described as having a "suggestion of a schistose texture."[2] Observations such as these, though seemingly unimportant, may nevertheless have considerable importance in connection with the movement of a mass with very little interstitial liquid. It may well be, also, that in the movement of a mass with a small amount of interstitial liquid lies the secret of the formation of some monomineralic masses of extreme purity. Such movement when it caused a crushing of crystals at their points of contact would necessarily imply a flowing away of some liquid. Continuance of this action might, under certain conditions, result in a squeezing out of the interstitial liquid as from a sponge.

Rocks made up almost exclusively of albite or oligoclase are known, but there is usually evidence, if only of a collateral nature, that solutions have played a prominent part in their formation. Though often occurring as dikes there is never any reason for believing that these materials have ever been molten as such. And so it is with many masses of magnetite, indeed it is not impossible that practically any mineral might occur as dikes having a similar character and origin. Such an occurrence need not, however, affect one's belief that, as a rule, monomineralic rocks are crystal accumulations analogous to the great anorthosite masses and having the characteristics corresponding thereto.

It will be noted that nowhere in the foregoing discussion has an appeal been made to the remelting of the masses of crystals once accumulated. While the writer would not go the length of stating that such action never takes place, he would nevertheless consider that it must be of very exceptional occurrence. It has been shown that the monomineralic rocks are best explained without the aid of the doctrine of remelting, and many of the broader generalizations of igneous geology are opposed to it. For example, the parallelism between sequence of intrusion and sequence of con-

[1] "L'Oural du nord I," *Mem. soc. phys. et d'hist. nat. de Genève*, XXXIV (1902), Fasc. 2, p. 101.

[2] Warren, Allan, and Conner, *Am. Jour. Sci.* (4), XLIII (1917), 75.

solidation is altogether too close to permit one to consider remelting an important factor. Remelting would almost certainly destroy all law and order in this matter. Harker has recently expressed a belief to the contrary, pointing out that the remelting of a solidified mass with basic material at the bottom and acid at the top might take place from the bottom upward.[1] Possibly it might, and in an undisturbed crust it would realize the common sequence of intrusion, but in an earth's crust subject to faulting, folding, and overthrusting it may be doubted whether any regularity would be observed. Disturbance of the stratified mass would often put some of the basic material on a level with or even on a higher horizon than some of the acid material. The remelting of such a disturbed mass would not give rise to any significant regularity in the intrusive sequence.

A CONSIDERATION OF THE CRITERIA FOR THE RECOGNITION OF ONCE MOLTEN ROCKS

If we pass in review the development of ideas concerning igneous or once molten rocks we find them first clearly recognized in surface lavas. It was natural that it should be so, for here we have rocks that, judging from their relations to their surroundings, have evidently flowed as a liquid, and that are being duplicated in flows from active volcanoes at the present day. Then we find a few coming to believe that other rocks, usually quite distinct in appearance and occurring as deep-seated masses only bared by erosion, really are made up of the same material, the difference in appearance being principally due to the difference of conditions under which solidification took place. After much controversy this belief gains general acceptance, especially as a result of the accumulation of facts proving the essential identity of these deep-seated masses with volcanic flows. Originally, then, it was this correspondence of plutonic rocks with volcanic rocks that gave geologists the right to consider them once molten or igneous rocks. Simultaneously with the development of this view numerous facts corroborative of it accumulated, important among these being the manner in which the plutonic masses sent tongues into the surrounding rocks, and

[1] *Journal of Geology*, XXIV (1916), 556.

the light which the microscope threw on the process of crystallization of their mineral constituents, which evidently took place precisely as it should if they were once molten. Eventually, these corroborative facts came to be the criteria for the recognition of an igneous or once molten rock and, at present, in actual practice it is almost exclusively on the basis of the microscopic structure that a rock is placed as igneous or not. Thus judged, the monomineralic rocks are unquestionably to be considered as once molten, but if we revert to the original criteria we find that in some respects they fail to qualify. In the matter of sending tongues into surrounding rocks we find them scarcely typical, and as far as occurrences as lavas are concerned we find them wholly wanting. This apparent discrepancy is due to the fact that we have not made our distinctions fine enough. These rocks were formerly molten, but they were never molten as such. When molten they were part of a complex solution. Monomineralic rocks therefore afford the strongest justification for believing that crystallization controls differentiation. If differentiation took place in magmas wholly liquid, it would seem that all plutonic rocks should have their effusive equivalents. An examination of any table of classification of igneous rocks on a mineralogic basis shows, however, a decisive tendency for plutonic rocks to vary more widely than do effusives, especially among basic rocks, and especially in this matter of running to marked richness in one mineral. This fact would have little significance if it were a fairly common feature of plutonic rocks to lack an effusive equivalent, but it becomes of the greatest significance in connection with the manner of origin here advocated for the monomineralic rocks when it is realized that in this respect the monomineralic rocks stand alone.

VOLUME AND AGE RELATIONS OF MONOMINERALIC ROCKS

Of the monomineralic rocks anorthosite is the only one that occurs in any great amount. The actual volume of pyroxenite and peridotite exposed at the surface of the earth appears to be insignificant.[1] On account of the exceptional period required for the

[1] Daly's figures would indicate the order of magnitude (*Igneous Rocks and Their Origin*, p. 44).

sorting of plagioclase crystals anorthosite can form only from very large masses of magma that cool with great slowness, or if from masses of more moderate size these must be deep-seated. The anorthosite of the large masses normally belongs below the granitic zone so that, whether formed in very large bodies or in bodies of more moderate size, it is an especially deep-seated rock. Peridotites and pyroxenites by reason of the relative ease of sorting of these heavy minerals can form from moderate masses and at moderate depths, and are therefore of widespread occurrence and of general distribution in the geologic column though never exposed in large masses. Anorthosites, on the other hand, being essentially deep-seated are exposed only in terranes that have suffered, locally at least, exceptionally deep erosion, the pre-Cambrian and perhaps early Paleozoic. According to the writer's opinion there are probably large masses of peridotite and pyroxenite, but these have not been exposed at all for the same reason that anorthosite is exposed only in the older terranes. These peridotites and pyroxenites are, as it were, the complements of the granites, which in virtue of their low density are so abundantly exposed. Many will, no doubt, consider the opinion that there are large unexpected masses of pyroxenite and peridotite a pure assumption, and it is quite true that some assumption must be involved in the formation of opinion concerning inaccessible portions of the earth. Nevertheless, an assumption based on analogy with many completely accessible bodies showing density stratification should surely be given a preference over an assumption, tacit or otherwise, that the kind of rocks exposed in any body extend downward indefinitely, which is based merely on lack of evidence, one way or the other, for that particular body. However this may be, it is certain that anyone who believes that anorthosite is a differentiate of gabbroid magma, as most petrologists do, must believe that there is an equivalent amount of pyroxenite somewhere, and if not exposed then presumably in inaccessible regions. At this point the hypothesis of crystal accumulation steps in with a rational explanation of the not infrequent lack of pyroxenite in anorthosite terranes, very difficult to account for on the doctrine of liquid differentiation. Being an accumulated mass of crystals, pyroxenites usually remain sub-

stantially where formed. If liquid they could not fail to be represented very prominently in all anorthosite terranes, for the liquid would be freely intruded into overlying rocks at every disturbance experienced by them.

SUMMARY

Anorthosites are made up almost exclusively of the single mineral plagioclase, and in virtue of this fact they present a very special problem in petrogenesis. The conception of the mutal solution of minerals in the magma and the lowering of melting temperature consequent thereon is no longer applicable. Yet anorthosites give no evidence of being abnormal in the matter of the temperature to which they have been raised, in other words, they give no evidence of having been raised to the temperature requisite to melt plagioclase. A possible alternative is that they may never have been molten as such, and are formed simply by the collection of crystals from a cómplex melt, probably gabbroic magma. This possibility is in harmony with the expectations that grow out of experimental studies and for this reason a consideration of the likelihood that anorthosites have originated in the stated manner becomes imperative.

A consideration of the method whereby accumulation of plagioclase crystals might take place leads to the conclusion that the most promising is the separation by gravity of the femic constituents from gabbroid magma, while the plagioclase crystals, which are basic bytownite, remain practically suspended. Then, at a later stage, when the liquid has become distinctly lighter, having attained diorite-syenite composition, the plagioclase crystals, which are now labradorite, accumulate by sinking and give masses of anorthosite, at the same time leaving the liquid out of which they settle of a syenitic or granitic composition.

Some of the consequences of this manner of origin of anorthosite are as follows. Typical anorthosite, very poor in bisilicates, should not occur as small dikes, for a mass of accumulated crystals should have little invading power. A proportion of about 15 or 20 per cent bisilicates or other foreign material such as orthoclase and quartz should be necessary for the formation of small dikes. Typical anorthosite should for like reasons not occur as an effusive

rock, a rather large proportion of minerals other than plagioclase being necessary before such an occurrence would become possible. Anorthosite should be intimately associated with gabbro, but perhaps as intimately with syenite or granite. Anorthosites should commonly be labradorite rocks rather than bytownite or anorthite rocks.

A consideration of anorthosites with special reference to the Adirondack and Morin areas gives some reason for believing that anorthosites do show the requisite characters. For the Adirondack area especially, evidence is adduced favoring the possibility that there anorthosite and syenite may still occupy the relative positions in which they were generated by the process outlined, the Adirondack complex being interpreted as a sheetlike mass with syenite above and anorthosite below.

Other monomineralic rocks present essentially the same problem and are restricted in their occurrence in substantially the same manner if we consider especially those that approach most closely to the strictly one-mineral character. All of the monomineralic rocks do occur, however, as dikes and dikelike masses in essentially contemporaneous, congeneric, igneous rocks, a fact that may be interpreted as due to the intrusion of a heterogeneous, partly crystalline mass.

On the whole the inquiry gives considerable support to the belief that the monomineralic rocks, of which the anorthosites are perhaps the most important representatives, are generated by the process of collection of crystals under the action of gravity.